A posterior landmark-based registration-free method to identify pedicle screw trajectories for robot-based navigation: A proof-of-concept

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INTRODUCTION

Pedicle screw placement (PSP) is a frequent intervention in spine surgery. The use of robotic systems for PSP gains increasing attention, as they allow more accurate screw implantation. Current approaches pre-define screw trajectories in preoperative computer-tomography (CT) data and use registration for alignment with the intraoperative anatomy. In current approaches, screw trajectories are predefined in preoperative computed tomography (CT) data and adapted to intraoperative anatomy via registration. However, this approach is increasingly being questioned because the patient is exposed to radiation, the registration remains error-prone, and the screw trajectories cannot be adjusted intraoperatively. The EU Horizon 2020 project FAROS aims to develop a radiation- and registration-free robotic system for spine surgery. FAROS foresees using robotic ultrasound (US) to reconstruct a 3D model of the spine (see). However, existing planning approaches cannot be used for defining screw entry points (EP) and trajectories from this data, as US only allows to reconstruct the posterior surface of the spine and not entire vertebrae (Fig.1). In this work, we present a new approach capable of performing PSP EP and trajectory planning only based on posterior surface models.

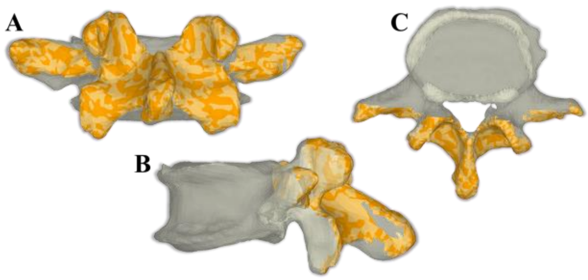

Figure 1. *3D model of the vertebrae (gray) and posterior surface of the spine visble in 3D US (orange) in posterior (**A**); sagittal (**B**); axial (**C**) views.*

MATERIALS AND METHODS

The EP in the lumbar spine is located at the junction between the pars interarticularis and the transverse process immediately lateral to the mammillary process, or at the bisection of a vertical line through the facet joints and a horizontal line through the transverse process. An optimal screw trajectory should be parallel to the upper-end plate in the sagittal plane and should not cross the midline in the axial plane. The screw is inserted perpendicular to the tangent of the spinous processes. There are rough reference values for the convergence of the screw (axial plane). As the EP moves laterally, the convergence of the screw increases from L1 to L5 and ranges from 5° (L1) to 45° (L5). Our method can be divided into the following steps: definition and adjustment of the sagittal, coronal, and axial plane (step 1), definition of the EP (step 2), and definition of the screw-tip point and thus determination of the trajectory (step 3).

Step 1. **Definition and fitting of anatomical planes**

Three orthogonal planes are created (sagittal, coronal, and axial plane) that will be aligned to anatomical landmarks of the 3D model as follows. First, the sagittal plane is aligned in the direction of the spinous process (Fig. 2 A, B). The screw-tip point is placed anterior of the anterior portion of the spinous process and lateral of the defined sagittal plane. Alignment of the axial plane is first performed in the posterior and then in the lateral view as follows. In the craniocaudal direction, the axial plane is aligned to the junction of the middle to caudal third of the transverse process (Fig. 2 C).

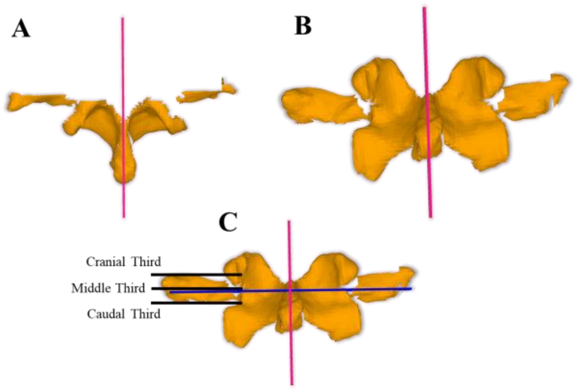

Figure 2. ***A and B:*** *Alignment of sagittal plane (pink) to spinous process on posterior mesh (orange) in axial (**A**) and posterior (**B**) views.* ***C:*** *Orientation of axial plane (blue) based on transverse process. Black lines indicate the border of cranial, middle and caudal third of transverse process.*

Subsequently, the sagittal angulation of the axial plane is defined on the lateral view. To this end, the coronal plane is first translated to be tangent to the transverse processes just laterally of the mammillary processes. Afterwards, a copy of the coronal plane (hereinafter defined as tangent- plane, yellow in Fig. 3A) is parallelly moved posteriorly until it touches the most posterior aspect of the spinous process while being tangent to the lordosis.

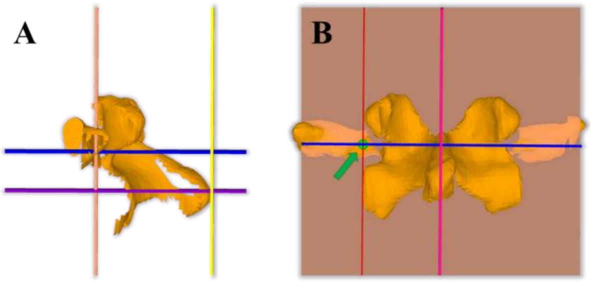

***Figure 3*. A:** (sagittal view) Orientation of axial plane (blue) in lateral view based on the tangent plane (yellow). Purple plane : parallel to axial plane (blue) through main axis of spinous process. Light brown plane: coronal plane. **B:** (posterior view) definition of entry point (green sphere and arrow).

Step 2. Definition of the entry point

The EP is defined as the intersection of the coronal plane, the axial plane, and a right/left parasagittal plane lateral to the mammillary processes or, if clearer visible, at the transition between the transverse process to the pars interarticularis (Fig. 3B).

Step 3. Definition of the screw-tip point

To identify the screw-tip point, additional planes are defined. Due to anatomical differences between levels, the definition varies for levels L1-L2 and L3-L5. First, a parasagittal plane is chosen tangential to the most lateral aspect of the facet joint (facet-plane, red in Fig. 4). For L1-L2, a parasagittal plane midway between the sagittal and facet planes (screw-tip plane, green in Fig. 4) is selected. For L3-L5, the screw-tip plane lies medially at one-quarter of the distance between the facet plane and the sagittal plane. Afterwards, the tangent plane is mirrored with respect to the coronal plane (anterior plane, black in Fig. 4). The screw-tip point is defined as the intersection of the anterior plane, the screw-tip plane and the axial plane. Lastly, the screw trajectory is defined as the direction vector from the entry point to the screw-tip point.

Evaluation

We used retrospective CT data from 9 human lumbar spine cadavers for evaluation of the proposed method. For each lumbar vertebra (L1 to L5), *ground-truth screws* were planned using a surgery planning software (CASPA, Balgrist, Switzerland). In a next step, the posterior surface was maked in Materialise 3-Matic using the brush function to mimic the reconstructed 3D US data (Fig. 1). The proposed method was then applied on the posterior surfaces using CASPA . Subsequently, the trajectories and screw tip points found with our method were compared with the ground-truth screw trajectory and screw tip point of each pedicle.

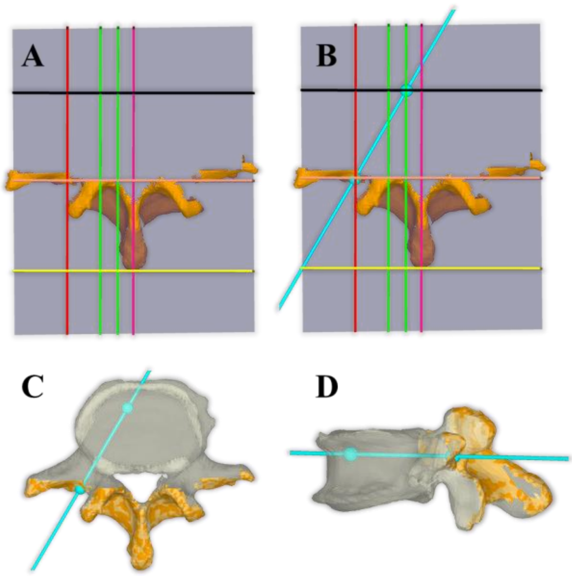

Figure 4. **A**: axial view with anterior plane (black), facet plane (red), screw tip planes (green, lateral for L1-2 and medial for L3-5), tangent plane (yellow), sagittal plane (pink), coronal plane (light brown) and axial plane (blue transparent); **B**: axial view with defined screw tip point, EP and trajectory. **C, D**: defined trajectory on axial and sagittal view, respectively.

RESULTS AND CONCLUSION

The average 3D deviation from the screw-tip point defined by the new method compared to the *ground truth* tip point was 4.06 mm (± 2.62 mm) in our analysis. The average 3D angular deviation was 4.74° (± 3.48°).

In this study, we proposed a novel method for defining the screw trajectory during spinal surgery only requiring a 3D-reconstruction of the posterior surface of the spine. The preliminary results proved feasibility on simulated data based on CT. The evaluation on real data obtained from robotic ultrasound will be addressed in future work.

Table .1. *Accuracy of our methods compared to ground truth data given for the screw-tip points and trajectories.*

	Screw-tip-points [mm]	Direction [°]
overall	4.06 (± 2.62)	4.74 (± 3.48)
L1	6.09 (± 1.59)	7.44 (± 4.50)
L2	4.90 (± 1.68)	5.91 (± 3.74)
L3	1.76 (± 1.64)	2.58 (± 1.34)
L4	2.67 (± 2.09)	3.03 (± 0.92)
L5	4.88 (± 3.76)	4.74 (± 4.26)

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